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Secondary school students' misconceptions in genetics: obstacles to learning and to address complexity

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ABSTRACT

'Complex thinking' has become an essential skill for understanding current societal issues. Complexity, inherent in the living world, is part of our daily lives. Genetics, a complex discipline, occupies an increasing place in our society, notably through free access to online genetic tests. Our research questions the ability of students, at the end of their school journey, across all tracks, to grasp genetics in all its complexity. Is this discipline approached in such a way as to anchor fundamental knowledge essential to awaken the learner to a reality full of unexpected events and uncertainties? A first study examined the misconceptions conveyed by the education frames of reference, school curriculums, and textbooks used by French-speaking Belgian teachers (the prescribed). This analysis highlighted that the prescribed reflects little, if at all, the complexity of genetics and reinforces misconceptions. Two surveys were then conducted in order to analyse the practices of science teachers in the third degree of secondary education in French-speaking Belgium (the taught) and the knowledge of students leaving secondary school (the learned). These surveys reveal that a rather reductionist and deterministic approach, poorly contextualised, insufficiently updated (didactic transposition delay), and little nuanced persists in the teaching of genetics.

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Introduction

The societal challenges we face daily are linked to multifactorial issues, requiring a nuanced approach. In the face of this complexity, society often resorts to simplistic solutions, aiming to ease the concerns of citizens seeking certainty and confidence. A clear example of this trend can be found in the field of genetics and the availability of online genetic tests. These tests seem to offer a simplified answer to complex questions about our origins, identity, and health.

This simplification is reinforced by popular media. Ley, Jankowski, and Brewer (2012) demonstrate that forensic crime shows like the series CSI (Crime Scene Investigation) tend to present DNA tests as common, quick, useful, and reliable, contributing to a distorted public understanding of genetics. Similarly, Muela and Abril (2014) argue

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that films can reinforce misconceptions, thereby hindering learning and promoting inaccurate views of genetic science.

These representations have significant consequences. Carver et al. (2017), using the PUGGS (Public Understanding and Attitudes towards Genetics and Genomics) questionnaire, identified widespread misunderstandings among students. Gericke et al. (2017) showed that belief in genetic determinism, defined as the idea that genes solely determine traits, is influenced by social and educational factors. Cross-national studies confirm that such beliefs vary by country and trait (Gericke 2021). More recently, Casanoves de la Hoz et al. (2022) and Del Re (2024) observed similar misconceptions among pre-service teachers and university students, respectively.

Donovan et al. (2021) emphasise that these misconceptions often reinforce genetic essentialism, the belief that an individual's identity, behaviour, or destiny is determined primarily by their genes. This perspective tends to overlook the complex interplay between genetic, environmental, and social factors. To counter such deterministic narratives, they advocate for the development of genomics literacy, which enables individuals to critically interpret genetic information.

Moore, Kampourakis, and Gericke (2025) identify three interrelated misconceptions: genetic essentialism (genes define who we are), genetic determinism (genes solely determine traits), and genetic reductionism (genes provide the ultimate explanation for phenotypes). These oversimplified views hinder a nuanced understanding of genetics and must be explicitly addressed in education.

Textbooks also contribute to the persistence of these misconceptions. Forissier and Clément (2003) found that when textbooks present a single causal relationship between genotype and phenotype, teachers relying on these materials often adopt this same reasoning. Castéra, Bruguière, and Clément (2008) observe that French secondary school biology textbooks frequently associate genetic diseases with a direct, linear, and causal model of genetic determinism.

Comparative studies confirm these trends. Agorram et al. (2011) highlight conceptual inconsistencies in Mediterranean countries, while Gericke et al. (2014) and Wahlberg and Gericke (2018) identify similar issues in other regions, including a lack of contextualisation in the presentation of key genetic concepts. Experimental studies, such as that of Drits-Esser, Bass, and Stark (2014), show that well-designed instructional materials, particularly those focused on human epigenetics, can support conceptual change and promote more accurate understandings of genetics.

Education plays a central role in addressing these challenges. Atlan (1999), a biophysicist, opposes the old paradigm of 'all-genetic' to the new paradigms of emergence and complexity. However, as Rumelhard (2005) noted, old paradigms often persist and form obstacles to learning new ones. Boerwinkel, Knippels, and Waarlo (2011) stress the importance of helping students to understand the various complex aspects of genetic tests. Duncan, Rogat, and Yarden (2009) propose a learning progression to deepen students' understanding of modern genetics.

Morin (2016) argues that contemporary education fails to adequately address complexity, leading to fragmented knowledge and biased truths. These partial truths, amplified by media and social networks, contribute to widespread misconceptions. In response, Gericke and Smith (2014) and Stern and Kampourakis (2017) call for genetics education that reflects the epistemological and conceptual shifts of the post-genomic era, emphasising the need to address learning difficulties and conceptual challenges.

Clément and Forissier (2000) point out that the complexity of life can no longer be reduced to genetic determinism alone and that, therefore, its study requires confronting other mechanisms, such as epigenetics, to analyse the construction of phenotypic traits. Epigenetics provides a conceptual framework that bridges the traditional dichotomy between nature and nurture, offering students a more dynamic and systemic understanding of gene expression and phenotype development. It highlights how environmental factors can influence gene activity without altering the DNA sequence itself, thus challenging deterministic interpretations of genetic information (Gericke and McEwen 2023; Gericke et al. 2021; Zudaire and Fraile 2021). These insights are essential for fostering complex thinking and for helping students grasp the multifactorial nature of biological traits.

To support this integration, a pedagogical framework for teaching epigenetics – referred to as *epigenetic literacy* – was developed by Gericke and McEwen (2023) through international expert collaboration. This framework identifies key conceptual and sociocultural themes that help students understand gene-environment interactions and the dynamic nature of gene expression. It emphasises the importance of introducing epigenetics to connect molecular biology with broader social and environmental contexts (Gericke 2021). Zudaire and Fraile (2021) argue that integrating epigenetics into secondary science education requires careful pedagogical planning and a gradual introduction of its conceptual complexity.

The role of teachers is therefore critical. According to Aivelo and Uitto (2019), teachers' choices regarding content and their approaches to controversial or sensitive topics, such as genetic testing, heredity, or behavioural traits, play an important role in shaping how students engage with and make sense of genetics. Moreover, Thörne and Gericke (2014) show that the way teachers talk about proteins in genetics lessons often lacks clarity and completeness, which may contribute to students' simplified or mechanistic views of gene function.

The present study aims to analyse the misconceptions conveyed by the education frames of reference, school curriculums, and textbooks used by French-speaking Belgian teachers (the prescribed), the practices of biology teachers in the third degree of secondary education in French-speaking Belgium (the taught), and the knowledge of students leaving secondary school (the learned).

To guide this analysis, the research focuses on eight key genetic concepts: penetrance, expressivity, polygenism, polyallelism, gene-protein relationships, biological complexity, environmentally influenced factors, and cloning (see explanatory Box). These concepts were selected because they present essential entry points for understanding the multifactorial nature of genotype-phenotype relationships and for challenging deterministic interpretations of genetics.

While certain concepts among the eight are regarded as advanced, they are increasingly recognised as necessary for fostering conceptual change, even among students with limited exposure to science. In particular, the concepts of expressivity and penetrance of phenotypes are fundamental to understanding (epi)genetics. Expressivity refers to the variability in the severity of a phenotype resulting from a given genotype, while penetrance denotes the proportion of individuals with a particular genotype who actually express the associated phenotype. These concepts are consistently addressed in the molecular genetics research literature, notably in the work of Rezsöhazy (Odelin et al. 2023; Remacle et al. 2004), who also emphasises their importance in grasping the complexity inherent in genetics.

Polygenism and polyallelism further illustrate the diversity and the interaction of genetic contributions to traits, while the gene-protein relationship underscores that not all genes code for proteins, complicating simplistic views of gene function. The inclusion of environmentally influenced factors and the concept of biological complexity further supports a systems-thinking approach, while the example of cloning, often misunderstood, helps illustrate that genetic identity does not equate to phenotypic identity.

These concepts align with the broader goal of promoting epigenetic and genomic literacy and are consistent with international recommendations for integrating complexity into secondary biology education (Donovan et al. 2021; Stern and Kampourakis 2017; Zudaire and Fraile 2021). They provide a coherent framework for evaluating how complexity is, or is not, addressed across the prescribed, taught, and learned dimensions of genetics education.

Finally, this selection raises important pedagogical questions about which complex biological ideas can and should be introduced in secondary education, and under what conditions they can be made accessible and meaningful to students. By focusing on students' understanding of these key genetic concepts, this study provides an initial diagnostic perspective on how complexity is perceived and processed at the learner level. These insights are intended to inform future research and contribute to the design of a didactic device that will help improve the development of complex thinking in students, starting from the genetics course.

Methods

We analysed the education frames of reference of the Wallonia-Brussels Federation (before and after the 2014 decree), the school curriculums of the subsidised private and public French-speaking Belgian education systems across different tracks (6th General Transition: basic sciences (one 50-min biology period each week) and general sciences (two 50-min biology periods each week); 5th Technical Transition: scientific education; 5th Technical Qualification and 6th Professional: scientific training) as well as the Dutch-speaking Belgian education system (Vlaams Verbond van het Katholiek Secundaire Onderwijs, Federatie Steinerscholen en Onderwijs van de Vlaamse Gemeenschap), the scientific high school in Italy (liceo scientifico), European schools in French, high schools in Ireland (High School, Leaving Certificate – Ordinary Level and Higher Level), and high schools in Great Britain (Sixth Form, Advanced Subsidiary AS and Advanced A-Levels). Thus, we examined different educational systems, namely the continental European system (education in Belgium and Italy), the international system (education in European schools), the Anglo-Saxon system (education in Ireland and Great Britain), and another system (the Steiner system, Federatie Steinerscholen).

Regarding textbooks, we analysed the books from the three most used publishers in Belgium (Van In, De Boeck, and Plantyn), one in general sciences, 'BIO6' by Van In, and two in basic sciences, 'Biologie 6' by De Boeck and 'Essentia 6 Biologie' by Plantyn.

Each education frame of reference and school curriculum were analysed and classified according to four criteria:

- Epigenetic mechanisms are mentioned, and the term ‘epigenetics’ is used,
- Epigenetic mechanisms are mentioned but the term ‘epigenetics’ is not used,
- Epigenetic mechanisms are not mentioned but, by extrapolation of what is required in the education frame of reference/school curriculum, the teacher could talk about them,
- Epigenetic mechanisms are not mentioned.

In the textbooks, we searched for the term ‘epigenetics’.

In the education frames of reference, school curriculums, and textbooks, we identified excerpts that promote the construction of misconceptions in genetics.

To interpret the misconceptions identified in school curriculums and textbooks, we refer to the conceptual change perspective developed by DiSessa (2014). This approach considers misconceptions not as isolated errors, but as context-sensitive knowledge elements that may be activated inappropriately or lack integration. This perspective, known as *knowledge in pieces*, emphasises the need to reorganise and connect these elements rather than replace them wholesale.

Testing tool

A survey was conducted among French-speaking Belgian students and teachers to assess the knowledge and misconceptions of learners and the teaching practices in genetics and epigenetics.

A first questionnaire aimed at students in the third degree of secondary education and at the beginning of first-year bachelor students (Appendix 1) was designed to identify their misconceptions, knowledge, and epistemological obstacles in (epi)genetics.

Informed consent was obtained from the participants, who acknowledged that they were informed about the nature of the investigation, understood that the data collected would remain strictly anonymous, and that the investigator guaranteed this anonymity.

The questionnaire includes multiple-choice questions about their knowledge of genetics and their beliefs, as well as statistical questions such as gender, age, academic track, and educational network.

A second questionnaire aimed at biology teachers in the third degree of secondary education (Appendix 2) was designed to better understand what is already taught in (epi) genetics (what is prescribed and/or actually seen or applied) as well as the epistemological posture of the teachers.

The teachers were informed that the data collected through this questionnaire would only be used for the purposes of the mentioned research. They could also opt to be contacted for further information about their teaching practices and to receive the survey results by providing their contact details.

Through the questionnaire, we measured variables such as the teachers’ propensity to provide valid examples of the influence of the environment on gene expression. We also collected variables such as gender, age, training, career length in teaching, fields of study, and educational network.

The dissemination took place from May 2022 to October 2022 and in August 2023 for students, and from May 2022 to December 2022 for teachers. Invitations to complete the online questionnaires were sent by email to schools in the Wallonia-Brussels Federation (of all networks) and to some higher education professors to submit the questionnaire to their first-year bachelor students at the beginning of the academic year. We will consider these students as equivalent to those in their final year of school, as they will also rely on the knowledge acquired during their schooling to respond to the questionnaire.

The items included in the student questionnaire were developed by the researchers, based on a conceptual framework grounded in current literature in genetics education and molecular biology. Each item was designed to probe understanding of a distinct concept (e.g. penetrance, expressivity, polygenism, gene-protein relationships), rather than to measure a single concept. A correlogram analysis was performed to explore potential relationships between student's responses. The response formats (multiple-choice) were chosen to reflect both factual knowledge and conceptual reasoning, in line with the study's epistemological and didactic objectives.

To ensure content and cognitive validity, the questionnaire underwent a two-step validation process:

- Expert review: The items were reviewed by internal and external researchers with expertise in genetics, sciences education, and epistemology. This process ensured that the questions were scientifically accurate and reflected the conceptual goals of the study.
- Readability testing: two experienced biology teachers not involved in the project reviewed the questionnaire to assess clarity, language accessibility, and appropriateness for the target audience.

Due to institutional constraints in the Belgian context, it was not feasible to conduct a pilot study with students prior to full deployment. However, the expert validation process was considered sufficient to ensure the instrument's relevance and interpretability.

Sample

To reach a wide audience, the questionnaires were distributed through school principals, who relayed the survey to their teachers. The questionnaires were designed to be completed online via the Eval&Go software. In total, 55 biology teachers and 541 students responded to the surveys, with 71%, i.e. 39 teachers, and 87%, i.e. 468 students, completing them in full (337 students at the end of the 2022 school year and 131 students at the end of the 2023 school year). Regarding the students, this analysis will be limited to the 332 students who answered the entire questionnaire and who are from French-speaking Belgian education, from the educational networks, public education (Wallonia-Brussels Education – WBE) and subsidised private education (SeGEC/FELSI), and from the General Transition tracks in basic sciences (one 50-min biology period each week) (118 students) and general sciences (two 50-min biology periods each week) (214 students), as the other networks and tracks are underrepresented in the sample.

Results

In this section, we first present the results of the analysis of education frames of reference and school curriculums (the prescribed). Then, we analyse the responses to the surveys conducted with teachers and students (the taught and the learned).

The prescribed

The analysis of the education frames of reference of the Wallonia-Brussels Federation and the Belgian, Italian, Irish, and English school curriculums allowed us to observe that complexity in genetics does not appear in the prescribed content. Only the school curriculums of the Dutch-speaking Belgian education system and English schools, at A level (Advanced Level, designed to prepare students for higher education), mention epigenetic mechanisms.

In the education frames of reference, school curriculums, and textbooks used by French-speaking Belgian teachers, we can observe that genetics is mainly considered as the heredity of traits conditioned by genes. Few excerpts from textbooks mention epigenetic mechanisms; in the cognitive skills to be developed in students according to the school curriculums, we can see a tendency towards simplification and decontextualization in cognitive skills (Appendix 3). To further illustrate this point, a table (Appendix 4) shows how selected examples from textbooks can be analysed through the lens of the *knowledge in pieces* framework (DiSessa 2014).

Only the cognitive skills '*Illustrate with an example that the environment can modify the expression of certain phenotypes*' (in 6th General Transition, basic sciences) and '*Show the influence of the environment on the expression of certain phenotypes*' (in 6th General Transition, general sciences) could allow teachers to address epigenetic mechanisms, but they do not guarantee that teachers will talk about them because phenotype modifications do not always depend on epigenetic mechanisms. Indeed, the school curriculums propose simple examples such as the colour of hydrangeas or the coat of Siamese cats. However, these examples do not illustrate epigenetic mechanisms.

In hydrangeas, flower colour varies with soil pH due to changes in aluminium ion availability, which directly affects pigment chemistry without altering gene expression (Yoshida et al. 2021). In Siamese cats, coat colour is influenced by temperature-dependent enzymatic activity: the enzyme responsible for melanin synthesis is only active in cooler regions of the body, such as the ears, paws, and tail, where it can function properly. In warmer areas, the enzyme is inactivated by heat, resulting in reduced pigment production. In both cases, the phenotypic variation is environmentally induced but does not involve epigenetic regulation. While some forms of phenotypic plasticity are mediated by epigenetic modifications – such as DNA methylation or histone remodelling – this is not the case here. As Carey (2012) emphasises, epigenetic regulation refers to molecular mechanisms that modulate gene expression without altering the DNA sequence. These mechanisms can be mitotically stable but are generally reversible and context dependent. It is therefore essential to distinguish between plastic responses that involve epigenetic regulation and those do not, in order to avoid conceptual confusion and preserve the specificity of the term 'epigenetics'.

The cognitive skill '*Show the importance of homeotic or architect genes in the development of a living being*' is to be addressed in the 'evolution' part of the French-speaking Belgian education frame of reference in general sciences, whereas, if integrated into the genetics part, it could allow addressing of the epigenetic mechanisms involved in cellular differentiation. Today, we can no longer talk about heredity without mentioning the epigenetic mechanisms that are continuously present to regulate gene expression.

The taught and the learned

Representativeness of samples and significance of variables

Before analysing the responses of teachers and students to the surveys, the question of the representativeness of the samples can be raised.

To compare our samples to the target population, we used the values provided by the Fédération Wallonie-Bruxelles.

According to these indicators, considering only subsidised private education and public education (Wallonia-Brussels Education – WBE) networks, in 2022, the distribution of the school population in mainstream education in 2021–2022 is 72.4% in the subsidised private network and 27.6% in the WBE network. In the sample, 89.5% of respondents are from the subsidised private network, and 10.5% from the WBE network. We can estimate that the student sample is not perfectly representative of the population of French-speaking Belgian mainstream education (according to the 2021–2022 data). Since the basic education frames of reference are common, we can still link the misconceptions of students at the end of their schooling to the reference school curriculum according to the most represented networks and tracks in the sample, namely, the WBE and subsidised private networks and the General Transition tracks (GT) in basic sciences (BS) and general sciences (GS).

An analysis of variance (ANOVA, with $\alpha = 0.05$) indicates that only the variable 'track' has a significant influence on the students' results obtained in the eight knowledge questions. We can indeed observe better results among students in the general sciences track. This observation is not surprising, given that students in the general sciences track have two 50-min biology periods each week, while those in the basic sciences track have one 50-min biology period each week.

The variables 'year' (students at the end of the 2022 or 2023 school year), 'gender', 'age', and 'network' do not have a significant influence on the results.

Regarding the teaching staff, according to the 2021–2022 data of French-speaking Belgian mainstream education, the average age is 43.5 years, and the percentage of women is 64% (for 36% men). Through the responses collected by the questionnaire, we find that the average age of respondents is 36 years, and 62% are women (38% men). Considering these two comparison variables, we estimate that the sample is representative of the population of teachers in French-speaking Belgium.

In terms of disciplinarity and functional representativity, the indicators of French-speaking Belgian mainstream education report that 460 teachers were engaged since 1 September 2015 and still active in January 2022 under the function teacher of science in upper secondary education (covering 4th to 6th years, which correspond to the three final years of secondary education). This figure includes all science disciplines (biology, chemistry, physics) and all grades of the upper cycle. Since our study focuses particularly on biology teachers in 5th and 6th years, the actual target population is smaller and not precisely quantified in official statistics. Therefore, while the sample size may appear modest, it represents a non-negligible portion of the relevant teaching population.

An analysis of variance (ANOVA, with $\alpha = 0.05$) indicates that none of the considered variables (namely, gender, age, training, seniority, course/track, network, opinion on the 2014 reformulation of a cognitive skill related to epigenetics) has a significant influence on the teachers' propensity to provide valid examples of the influence of the environment on gene expression.

Students' interests and teaching practices

We can observe that a significant percentage of students express an interest in online genetic tests. Among the 373 students who responded (of all networks and tracks), 79% express the desire to take a genetic test if they have the opportunity (Appendix 1, question 4). Additionally, of the 371 students who answered the following questions, 32% report having already debated the free use of genetic tests as an activity proposed in the biology course (Appendix 1, question 3A). Among those who have not yet debated in class, 82% express the desire to do so (Appendix 1, question 3A).

On the teachers' side, among the 45 who responded, only 38% report talking to their students about the free use of genetic tests (Appendix 2, question 12).

Of the 371 students, 13% say they have already interacted with a genetics researcher (Appendix 1, question 3B), and 37% have already engaged in broader reflections involving other disciplines (e.g. ethical approach in religion or Education in Philosophy and Citizenship or argumentation in French) (Appendix 1, question 3E). Among those who have not yet experienced this type of activity in their biology course, 93% express the desire to interact with a genetics researcher (Appendix 1, question 3B), and 77% to engage in broader reflections involving other disciplines (Appendix 1, question 3E).

On the teachers' side, among the 44 who responded, 66% report not conducting didactic activities in collaboration with teachers from other disciplines (Appendix 2, question 19) due to lack of time (21%), because it is complicated to organise (55%), or because they do not perceive any added value (24%) (Appendix 2, question 21).

Students' misconceptions and knowledge

About 332 students from the WBE and subsidised private networks (SeGEC/FELSI) and the General Transition tracks in basic sciences (BS) and general sciences (GS) answered the eight knowledge questions, each question was worth one point, for a total of eight points. The correlogram analysis of the responses revealed a weak correlation between the different questions, indicating diversity in the understanding of the concepts addressed (see Figure 1).

Regarding the scores obtained for all the questions, the median for BS students was 2, while the median for GS students was 2.5, indicating a slightly above-average trend among GS students (see Figure 2).

6GT BS: $N = 118$ et $\mu = 1{,}8$.

6GT GS: $N = 214$ et $\mu = 2{,}5$.

The analysis of the results also highlighted significant gaps in the understanding of genetic concepts among students (see Figure 3). For example, a large percentage of students do not master the concepts of penetrance (80.7%) (Appendix 1, question 2A),

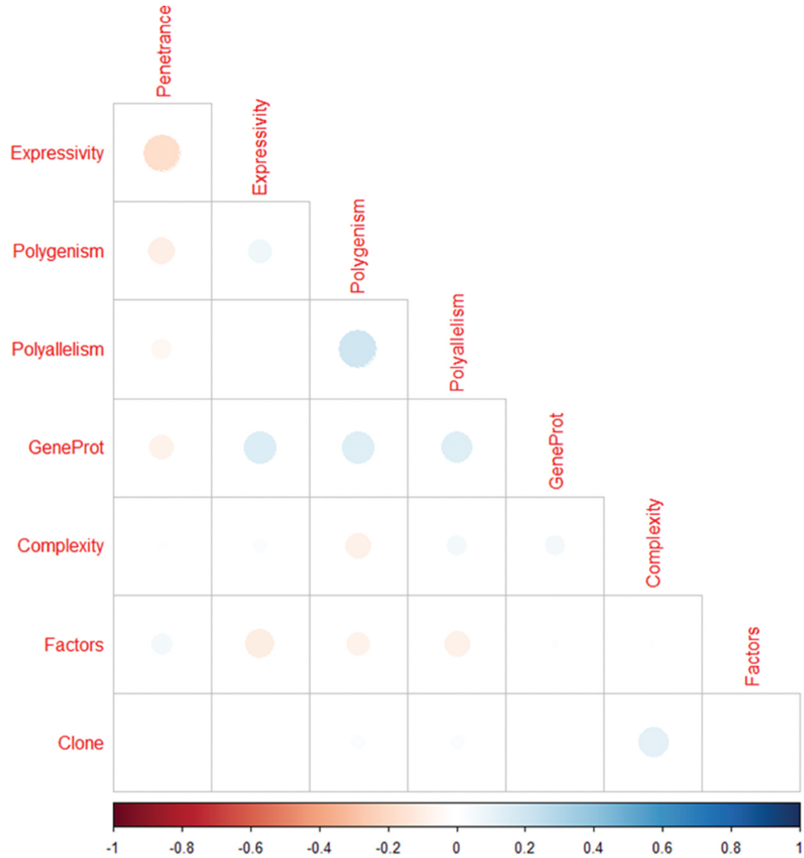

Figure 1. Correlogram of the eight knowledge questions (Appendix 1 - penetrance: question 2A; expressivity: question 2B; polygenism: question 5; polyallelism: question 6; GeneProt: question 7; complexity: question 8; factors: question 9; clone: question 10).

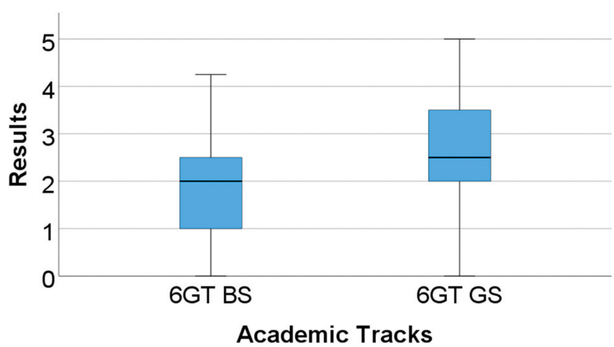

Figure 2. Results obtained for the knowledge questions out of 8 points, in 6GT basic sciences (BS) and general sciences (GS) from the WBE and subsidized private networks.

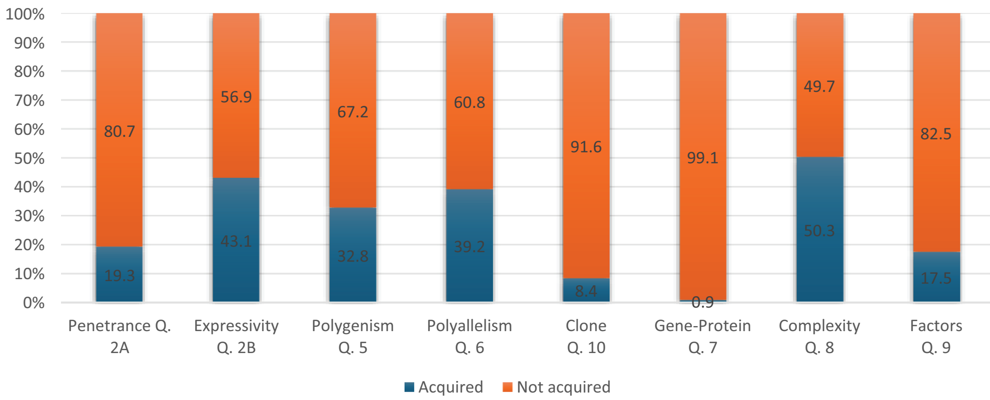

Figure 3. Concepts acquired or not acquired by students, related to the 8 knowledge questions.

expressivity (56.9%) (Appendix 1, question 2B), polygenism (67.2%) (Appendix 1, question 5), and polyallelism (60.8%) (Appendix 1, question 6). Regarding the concepts of penetrance and expressivity, among the 50 teachers who responded, 68% do not consider the influence of genetic variants on the penetrance and expressivity of a phenotype (Appendix 2, question 2).

Among the most common misconceptions of students, it is notable that many believe that each given genotype always results in the same phenotype (91.6% of students do not consider phenotypic variability between two clones) (Appendix 1, question 10). This result correlates with the finding that only 30% of teachers address phenotypic variability in situations involving two clones or when discussing the differences between identical (i.e. monozygotic) twins (Appendix 2, question 4).

Regarding the understanding of molecular processes, a large portion of students (99.1%) (Appendix 1, question 7) do not recognise that a higher portion of the genome is transcribed into RNA but not translated into proteins, nor that a gene can allow the production of one or several proteins.

Furthermore, nearly half of the students (49.7%) (Appendix 1, question 8) do not recognise that phenotypic complexity results from the interactions between genes, proteins, and RNA, but rather believe it depends on the amount of genetic information available.

Moreover, most students (82.5%) (Appendix 1, question 9) do not recognise that the environment, at various levels such as cells, organs, the individual, and the population, can influence the transcription and translation of genes.

This gap is likely due to a lack of knowledge and mastery of concepts among teachers.

Misconceptions and mastery of concepts among teachers

Indeed, it is interesting to note that among the 46 teachers who responded, only 15% consider the change in wording (in 2014) in the education frame of reference in basic sciences, regarding the influence of the environment on gene expression, to be of little relevance (Appendix 2, question 9); this change consisted of replacing the previous wording, which was '*illustrate with an example that the environment can* modify the expression of certain genes', with the new wording:

Example to illustrate that the environment can modify certain **phenotypes**		Example to illustrate that the environment can modify the expression of certain **genes**
65% ✓		53% ✗
43% ✓		29% ✗

Figure 4. Examples chosen by teachers to illustrate that the environment can modify certain phenotypes/the expression of certain genes.

'*illustrate with an example that the environment can modify the* expression of certain phenotypes'. These teachers justify their opinion by expressing concerns about the clarity of the new wording, noting a risk of not adequately addressing epigenetics. Furthermore, 80% of teachers claim to actively develop this cognitive skill with their students, while 20% do not (Appendix 2, question 6), with 44% of them citing a lack of mastery of these concepts as the reason (Appendix 2, question 8).

Among the teachers who develop this skill (80%), 43% use the example of the hydrangea and 65% use that of the Siamese cat to illustrate the influence of the environment on certain phenotypes, in accordance with the school curriculums (Appendix 2, question 7). However, when asked which examples they would use to illustrate a modification of gene expression, 29% of the 45 teachers who responded again chose the hydrangea and 53% the Siamese cat, although these examples are not appropriate (Appendix 2, question 11), see Figure 4.

Discussion

Students' interest in genetic testing

A significant percentage of students express an interest in online genetic tests. To address this interest and enable students to understand the ethical, social, and scientific implications of these advances, it would be beneficial to raise awareness and encourage teachers to address the topic of genetic tests in class, providing them with the necessary resources and support, and even offering them appropriate training, whether in initial or continuing training of teachers. Integrating this topic into school curriculums appears to be a potential solution to better address these issues.

The results indicate that a significant number of students have already debated or wish to debate the free use of genetic tests in biology class. This highlights the importance of creating discussion spaces to allow students to exchange ideas with peers and confront their opinions, while having the essential knowledge to support or question their reflections. Integrating bioethical dilemmas into genetics education, as suggested by Zohar and Nemet (2002), can foster both conceptual understanding and argumentation skills.

However, the study also reveals significant gaps in the understanding of certain fundamental concepts in genetics among the majority of students, but also among teachers. These gaps reflect persistent conceptual obstacles that have been widely documented in the literature. Misconceptions such as genetic determinism, genetic essentialism, and genetic reductionism remain prevalent. These simplified views obscure the multifactorial nature of biological traits and overlook the roles of environmental, epigenetic, and social influences (Moore, Kampourakis, and Gericke 2025).

Gaps in textbook content

The limited or superficial treatment of epigenetics in textbooks (e.g. only one mention in *Bio* 6, or relegated to a 'To learn more' section in *Essentia* 6 - Appendix 3) contributes to the persistence of deterministic models of heredity. From the perspective of conceptual change as described by DiSessa (2014), such omissions hinder the reorganisation of students' fragmented and context-sensitive knowledge elements (*knowledge in pieces*). A more explicit integration of epigenetic mechanisms could support conceptual change by challenging the linear gene-trait model and introducing gene regulation and environmental interactions.

Gaps among students

The observed gaps among students regarding key genetic concepts, such as penetrance, expressivity, polygenism, and polyallelism, underscore the urgency of more in-depth and nuanced teaching of these concepts. These gaps can be attributed to students' misconceptions, such as the belief that phenotypic complexity depends solely on the amount of genetic information available or that a given genotype always results in the same phenotype, which correlates with the finding that few teachers address phenotypic variability in individuals with the same genotype. These results corroborate those obtained by Castéra, Bruguière, and Clément (2008), who observed that direct and linear genetic determinism remains a widespread conception among students. These findings are also supported by more recent international research. For instance, Carver et al. (2017) and Del Re (2024) identified conceptual difficulties among students regarding gene function, genetic determinism, and the complexity of genotype-phenotype relationships. These misconceptions suggest that current educational approaches often fail to convey the multifactorial and probabilistic nature of genetic expression.

Gaps among teachers

Regarding the teaching of genetics, the results highlight several aspects that teachers face. Despite a willingness to develop in their students the ability to understand the influence of the environment on gene expression, many teachers encounter difficulties, particularly due to their own limited understanding of epigenetics. We observe a lack of nuance, likely attributable to a lack of knowledge of (epi)genetic concepts such as penetrance, expressivity, phenotypic variability, and epigenetic mechanisms. This aligns with findings by Casanoves de la Hoz et al. (2022), who showed that pre-service teachers frequently lack the conceptual tools needed to teach modern genetics and biotechnology. Furthermore, incorrect examples are used to illustrate the impact of the environment on phenotypes; there is confusion between phenotype modification and gene expression modification.

Forissier and Clément (2003) showed that teachers, relying on textbooks presenting a simple causal relationship between genotype and phenotype, often adopt similar reasoning. Although the notion of epigenetics became commonly accepted and integrated into research in the early 2000s (Wu and Morris 2001), textbooks reflect little or none of the recent scientific advances in genetics and epigenetics. Clément (2014) reveals that the didactic transposition delay, i.e. the time between the publication of research and its introduction into school curriculums or textbooks, is long in human genetics. This is predominantly due to the intense interaction of scientific knowledge with social practices, which underlies the persistence of innate values (Clément 2014). This observation is both significant and concerning. If this interaction were as intense as suggested, one might expect a shorter transposition delay. However, evidence indicates that this delay remains extended, implying that certain social practices may impede the rapid dissemination of new knowledge.

In addition to these social dynamics, delays in adopting innovative science instruction often stem from systemic constraints, including rigid curricular structures, the inherent complexity of scientific ideas, and the challenge of aligning instruction with students' evolving cognitive capacities. These factors make it difficult to implement approaches that support deep knowledge integration (Linn and Eylon 2011). This finding underscores the importance of examining both the social and institutional practices that shape the transmission of advances in human genetics to educational settings.

Towards a curriculum that embraces complexity

It thus appears crucial that school curriculums be redesigned to ensure precise and comprehensive learning of genetic concepts, emphasising the interconnections between DNA, RNA, proteins, and the intrinsic and extrinsic environment of the cell. Equipping students to have an overview of these different levels and their interconnections is essential to avoid attributing excessive determinism to genetic determinants.

Furthermore, Castéra and Clément (2014), examining conceptions of genetic determinism among teachers from 23 countries, observed that the level of teacher training influences their conceptions, with a decrease in innatism as the level of training increases. A study in Indonesia (Duda 2016) highlights the absence of a conceptual framework in the teaching of genetics, leading to poor understanding among students. These students retain previously acquired misconceptions, which are likely to be transmitted to their future students.

To address these challenges, targeted training programmes should be developed to strengthen teachers' pedagogical content knowledge (PCK) in genetics, combining content mastery with didactic strategies (van Driel, Verloop, and de Vos 1998). This would enable teachers to better support students in developing a nuanced understanding of genetics and in engaging critically with its societal implications.

Scientific knowledge significantly influences social practices, which explains the persistence of innate values (Clément 2014). In this perspective, Castéra and Clément (2014) suggest integrating 'genetic determinism' into biology teacher training, considering epistemological, social, and ethical approaches, as well as the possible interaction between knowledge, values, and social practices. This approach could promote more tolerant education by avoiding outdated stereotypes associated with innatism.

In correlation with this, Khalil, Shaaban, and Trouche (2016) highlight how teachers' conceptions of genetic determinism influence their teaching practices, while Gericke et al. (2017) emphasise the need to improve genetics education to reduce or prevent such beliefs. Gericke and McEwen (2023) further propose the concept of *epigenetic literacy* as a framework for integrating complexity into biology curriculums.

These gaps indicate that genetics is not addressed in all its complexity. A reductionist and deterministic approach persists, preventing learners from developing complex knowledge (Morin 2016) and fostering critical and responsible attitudes.

Therefore, education should aim to embrace complexity, enabling students to grasp the intricate interconnections between genetic, environmental, and societal factors. Such an educational shift is essential not only for fostering scientific understanding but also for preparing future citizens to navigate ethically and critically the societal challenges posed by advances in genetics.

Methodological limitations and sample representativity

This study has some methodological limitations. First, since the teacher questionnaire was distributed indirectly via the school principals, the number of teachers who received it is unknown. Therefore, the response rate cannot be calculated, and a self-selection bias is possible.

Second, while it is true that the subsidised private network is overrepresented, particularly in students from the General Transition tracks in basic and general sciences, this can be seen as an asset. Since these students are, in principle, better trained in genetics, the results observed can reasonably be generalised to students from other educational tracks.

Conclusion and perspectives

This study shows that if teachers limit themselves to what school curriculums recommend in terms of knowledge and skills in genetics, they risk conveying to their students a reductionist and deterministic cause-and-effect view that does not reflect the complexity of the discipline. Like the media, they risk promoting and reinforcing the construction of misconceptions such as genetic determinism, essentialism, and reductionism, which hinder the development of critical and responsible attitudes.

Identifying these misconceptions allows teachers to develop didactic teaching sequences that help overcome learning obstacles (Clément 2014). Indeed, all didacticians agree that students' erroneous representations should not be rejected and considered scientifically false but should rather be used as levers to identify epistemological obstacles. For example, learning the concept of a gene does not occur through a simple conceptual exchange but rather through an evolutionary process of assimilation and conceptual restructuring, reconciling previous conceptions with new ones (Lewis and Kattmann 2004; Venville and Treagust 1998).

In this perspective, the present study highlights key genetic concepts, such as penetrance, expressivity, phenotypic variability, and epigenetic mechanisms, which have proven particularly challenging for both students and teachers. These concepts provide essential entry points for exploring the multifactorial nature of genotype-phenotype relationships and for confronting persistent misconceptions in genetics education.

In line with the notion of *epigenetic literacy* as defined by Gericke and McEwen (2023), our findings support the integration of both scientific and societal dimensions of genetics into the curriculum. While previous work has focused on early secondary education, we propose the development of a didactic device specially tailored to upper secondary students (around age 18). This device would aim to foster a deeper conceptual understanding of genetics and promote critical, reflective and responsible attitudes towards societal issues related to this discipline. Such a device could include expert interventions, contextualised educational resources, and structured discussion spaces to promote epistemic engagement and conceptual change. Future research could explore the implementation and evaluation of this device in classroom settings, as well as its potential to bridge the gap between scientific advances and educational practice.

Furthermore, this research identifies needs in terms of teacher support or training. Genetic concepts are complex and difficult to teach and learn (Lewis and Wood-Robinson 2000; Lewis, Leach, and Wood-Robinson 2000). The results of this research could therefore guide political decisions and inform the teacher training curriculums that will be revised soon in French-speaking Belgium (reform of the initial training of upper secondary teachers starting in September 2025) as well as the school curriculums for secondary school students that will need to be designed based on the new education frames of reference that will be published soon.

In addition, while the questionnaire used in this study was not designed to measure a single concept, its structure, grounded in key conceptual distinctions in genetics, may serve as a pilot instrument for future research. It could be further refined and expanded to support the development and the validation of broader assessment tools in genetics education.

Ultimately, embracing the complexity of (epi)genetics in both teacher education and curriculum design is not just a pedagogical necessity, it is societal imperative for fostering scientifically literate, ethically aware, and critically engaged citizens.

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